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LCA FOR AGRICULTURE

Life cycle assessment of vegetable products: a review focusing on cropping systems diversity and the estimation of field emissions

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Abstract
Purpose Recent life cycle assessment studies for vegetable products have identified the agricultural stage as one of the most important contributors to the environmental impacts for these products, while vegetable production systems are characterized by specific but also widely diverse production conditions. In this context, a review aiming at comparing the potential impacts of vegetable products and analyzing the relevance of the methods and data used for the inventory of the farm stage appeared necessary.
Methods Ten papers published in peer-reviewed scientific journals or ISO-compliant reports were selected. First, a presentation of the selected papers was done to compare the goal and scope and the life cycle inventory data to the related sections in the ILCD Handbook. Second, a quantitative review of input flows and life cycle impact assessment (LCIA) results (global warming, eutrophication, and acidification) was based on a cropping system typology and on a classification per product group. Third, an in-depth analysis of the methods used to estimate field emissions of reactive nitrogen was proposed.
Results and discussion The heated greenhouse system types showed the greatest global warming potential. The giant bean group showed the greatest acidification and eutrophication potentials per kilogram of product, while the tomato group showed the greatest acidification and eutrophication potentials per unit of area. Main sources of variations for impacts across systems were yields and inputs variations and system expansion rules. Overall, the ability to compare the environmental impact for these diverse vegetable products from cradle-to-harvest was hampered by (1) weaknesses regarding transparency of goal and scope, (2) a lack of representativeness and completeness of data used for the field stage, and (3) heterogeneous and inadequate methods for estimating field emissions. In particular, methods to estimate reactive nitrogen emissions were applied beyond their validity domain.
Conclusions and recommendations This first attempt at comparing the potential impacts of vegetable products pinpointed several gaps in terms of data and methods to reach representative LCIA results for the field production stage. To better account for the specificities of vegetable cropping systems and improve the overall quality of their LCA studies, our key recommendations were (1) to include systematically phosphorus, water, and pesticide fluxes and characterize associated impacts, such as eutrophication, toxicity, and water deprivation; (2) to better address space and time representativeness for field stage inventory data through better sampling procedures and reporting transparency; and (3) to use best available methods and when possible more mechanistic tools for estimating Nr emissions.

Keywords Emissions · Greenhouse · Life cycle assessment · Open-field systems · Reactive nitrogen · Typology of cropping systems · Vegetable production

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1 Introduction

The year-round demand for a diversity of vegetables and fruits from Western markets has led to the development of complex

supply chains (farming, grading, packing, transport, storage, refrigeration, retailing…) often spread across distant countries. Particularly for off-season supply, this demand is also responsible for the development of artificial cropping systems under temperate climate (soilless and heated greenhouses) and of a range of cropping systems (from soilless and sheltered to open-field productions) in Mediterranean and tropical countries. The growing awareness regarding the environmental issues due to global food supply chains has now reached the fruits and vegetables sector, and the need for evaluating the different product origins and associated technologies has clearly been expressed.

The life cycle assessment (LCA) methodology was commonly used to assess the environmental performance of agricultural products over the last 15 years, revealing several scientific challenges due in particular to the use of land by farming systems, their interactions with their environment, their large variation in terms of soil, climate and practices, and the importance of local and regional impacts (Brentrup et al. 2004). Although the relevance of LCA to assess agricultural products was validated for a large number of agricultural products (Brentrup et al. 2001; Mila i Canals et al. 2006), its application to horticultural (i.e., fruits and vegetables) production systems was more recent and came with renewed and specific scientific challenges.

Since horticultural products and production systems are characterized by specific conditions of production and of interaction with their environment, but also by a large diversity of technologies and management practices, a review of the state of the art of LCA studies for horticultural products, as a recent object of study, appears necessary and timely. A recent review focusing on perennial crops (Bessou et al. 2013) already provided important insights regarding specificities of LCA applied to orchards (including fruit production). No relevant analysis has been made on LCA applied to annual and even shorter crop length products, e.g., vegetables. In available LCA studies of vegetable products, contribution analyses from cradle-to-grave and from cradle-to-retail studies revealed a significant contribution of postharvest stages (Sim et al. 2007; Andersson et al. 1998). However, authors widely agreed upon the field production stage being one of the greatest contributors especially to global warming, acidification, eutrophication, and toxicity potentials (Mila i Canals et al. 2008; Hospido et al. 2009; Andersson et al. 1998; Cellura et al. 2012b; Antón et al. 2005a). The importance and complexity of the field production stage in the LCA of vegetable products requires putting a particular emphasis on the analysis of the methods and data used for this stage.

Vegetable cropping systems show a huge diversity of farming and environmental conditions of production but also important specificities that largely impact the inventory, the associated on-field estimation methods, and the resulting LCA outcomes. Although this was already pinpointed in the literature, the methods and data used for the description of vegetable products and the calculation of their environmental inventory have never been reviewed nor have been their implications for LCA results. We focus in this paper on the cradle-to-harvest stages, including the production of agricultural inputs and the associated emissions. The objectives of this review were threefold, as follows:

1. To assess the state of the art of published LCA studies on vegetables including an original typology-based method, with a focus on data and methods used for the field production stage
2. To carry out a critical analysis of the methods used for the estimation of reactive nitrogen (N_r) emissions
3. To make recommendations in terms of practice and scientific challenges for applying LCA to vegetable cropping systems

2 Materials and methods

2.1 Selection of LCA studies and review process

A thorough literature search resulted in the identification of 17 papers published in peer-reviewed scientific journals or in ISO-compliant reports, which presented full LCA studies for vegetable products. Studies which did not involve multicriteria assessment (mainly those studies focused on energy and global warming potential) were excluded from our review, as well as reports which were not accessible on the Internet. A subsample of ten studies featuring consistent and well-described data for the modeling of cropping systems was found suitable for a qualitative and quantitative analysis.

Our qualitative review of goals and scopes (Sections 3.1 and 3.2) covered the main aspects described in the recent ILCD handbook related sections (European Commission 2010). Our quantitative review of LCI (Section 3.3) and LCIA results (Section 3.4) were based on an original typology described in the next section (Section 2.2). Results were also presented according to their product group and per reference. Across selected studies, only global warming potential, eutrophication potential, and acidification potential were homogeneously calculated following the CML methodology (Guinée et al. 2002) and could be selected for the quantitative analysis. The critical analysis (Sections 4.1 to 4.3) followed the main recommendations from the ILCD handbook. An in-depth analysis was also made on methods used for the estimation of nitrogen reactive emissions (Section 4.4).

2.2 Typology of cropping systems and aggregation of results

The cropping system generally results from the combination of a product's choice (targeted market), certain objectives of production (yield and quality), and a location. For vegetable products, this leads to diverse degree of artificialization in terms of protection status, heating, and growing media to overcome local natural constraints and reach the production objectives. To explore the cropping systems diversity from our panel of papers, we developed a typology of cropping systems, based on the following three main criteria: protection and heating status (heated or cold greenhouse or open-field), growing media (substrate or soil), and climate (temperate, Mediterranean, or tropical context). This typology was relevant to LCA as energy consumption is closely related to the greenhouse type and management (heated or not), while the growing media and the climate characteristics affect inputs rates, yields, and field emissions. This typology resulted in seven types named according to their characteristics. Greenhouse systems are either heated (GH-heat) or cold (GH-cold). Both systems can be led soilless on substrate (e.g., GH-heat-sub) or directly on soil (e.g., GH-heat-soil). Open-field cropping systems were classified according to their respective climate: temperate (OF-Temp), Mediterranean (OF-Med), or tropical (OF-Trop). Overall, 72 cropping systems were analyzed and grouped into 7 cropping system types.

Results were also aggregated by product group. Indeed, crop species have specific management requirements and potential yields, which affect their environmental performances. Across the ten studies, seven product groups were established, namely giant bean (Abeliotis et al. 2013), green bean (Romero-Gámez et al. 2012; Mila i Canals et al. 2008), broccoli (Mila i Canals et al. 2008), cauliflower (Martínez-Blanco et al. 2010), leek (de Backer et al. 2009), salad (Mila i Canals et al. 2008) and tomato (Torrellas et al. 2012; Boulard et al. 2011; Antón et al. 2005a; Martínez-Blanco et al. 2011; Martínez-Blanco et al. 2009). Finally, we presented the results per reference to analyze possible variations due to particular methodological choices by authors.

3 Presentation of LCA studies selected

3.1 Goal and scope

3.1.1 Intended applications

We can distinguish three objectives of the LCA studies reviewed as follows:

- Comparing different farming practices (Romero-Gámez et al. 2012; Torrellas et al. 2012; Martínez-Blanco et al. 2011; Martínez-Blanco et al. 2010; Martínez-Blanco et al. 2009; de Backer et al. 2009; Antón et al. 2005a)
- Comparing different product's origins such locally-grown products versus imported equivalent (Mila i Canals et al. 2008)
- Producing a reference for the environmental performance of a product in a given context (Abeliotis et al. 2013; Boulard et al. 2011)

3.1.2 Function and functional unit

Most papers studied the function of production expressed in mass of fresh or dry product (Abeliotis et al. 2013; Torrellas et al. 2012; Boulard et al. 2011; de Backer et al. 2009; Antón et al. 2005a). The production function could be associated to quality aspects either from a commercial standard (Romero-Gámez et al. 2012; Martínez-Blanco et al. 2009, 2010, 2011) or from a nutritional value perspective (Martínez-Blanco et al. 2010). The functions studied across those papers were often multiple including land occupation functions (Abeliotis et al. 2013; de Backer et al. 2009) and could refer to functions beyond the production, such as the consumption expressed in kilograms of vegetable consumed (Mila i Canals et al. 2008).

3.1.3 Comparison of systems

Across the ten reviewed papers, contrasted vegetable systems were studied. All studies had in common to present original inventories related to field production stages of vegetable products. Indeed, each cropping system was unique in terms of management and yield. These management and yield variations resulted from different modalities in terms of cropping system characteristics:

- The protection status: greenhouse versus open-field (Romero-Gámez et al. 2012; Martínez-Blanco et al. 2011; Mila i Canals et al. 2008), greenhouse type (Torrellas et al. 2012; Boulard et al. 2011), and greenhouse management (Torrellas et al. 2012; Romero-Gámez et al. 2012; Antón et al. 2005a)
- The growing media: substrate versus soil (Boulard et al. 2011; Antón et al. 2005a)
- The location: temperate, Mediterranean, or tropical contexts (Mila i Canals et al. 2008)
- The fertilization management, involving different types of fertilizer (mineral fertilizer vs. compost) and application rates (Martínez-Blanco et al. 2011; Martínez-Blanco et al. 2010; Martínez-Blanco et al. 2009)
- The production orientation: conventional, integrated, or organic (de Backer et al. 2009; Abeliotis et al. 2013)
- The product cultivar (Abeliotis et al. 2013)

Finally, management and yield variations also resulted from between-farms and within-year variability (Mila i Canals et al. 2008).

3.1.4 System boundaries and cutoff criteria

Reflecting those various functions but also the diversity of vegetable cropping systems studied, the system limits were diverse. As a rule, the system boundaries for cradle-to-farm gate LCA included agricultural operations (including greenhouse management) and on-field emissions due to fertilizers and pesticides within the foreground system ("foreground" refers here to the farm stage) and the production, transport, and use of buildings, machineries, and agricultural inputs within the background system ("background" refers to processes before the farm stage). Several additional stages were recorded across studies. Eight studies explicitly included the waste treatment phase (Torrellas et al. 2012; Romero-Gámez et al. 2012; Boulard et al. 2011; Martínez-Blanco et al. 2009, 2010, 2011; Antón et al. 2005a). Six studies explicitly included the nursery phase (Torrellas et al. 2012; Boulard et al. 2011; Martínez-Blanco et al. 2009, 2011; de Backer et al. 2009; Antón et al. 2005a). Boulard et al. (2011) included the packaging phase occurring on the farm, and Mila i Canals et al. (2008) included fuel consumption related to the transport of workers. Some studies included the biogenic fixation of atmospheric carbon dioxide in plants (Mila i Canals et al. 2008) or in soil after compost application (Martínez-Blanco et al. 2010; Martínez-Blanco et al. 2011). We also noticed some punctual omissions, such as transport and packaging of agricultural inputs (Romero-Gámez et al. 2012), building and machinery production and transport (Abeliotis et al. 2013; de Backer et al. 2009), pesticides production and associated field-emissions (Torrellas et al. 2012; Martínez-Blanco et al. 2011; Martínez-Blanco et al. 2010), or quite often simply pesticides field emissions (Abeliotis et al. 2013; Romero-Gámez et al. 2012; Martínez-Blanco et al. 2009).

Several procedures were described regarding multifunctional processes and flows crossing the cropping system limits. Martínez-Blanco et al. (2009) and following papers (Martínez-Blanco et al. 2010, 2011) assigned avoided burdens from dumping organic wastes to their system using compost. Torrellas et al. (2012) presented two scenarios regarding the expansion of their heated greenhouse tomato system to cogeneration of heat and electricity: (1) avoided burden from producing the electricity used for the system using cogeneration, and (2) allocation of gas consumption for greenhouse heating based on energy criteria. In Martínez-Blanco et al. (2011) and in Boulard et al. (2011), the allocations of compost and amendments were based on plant uptake. The allocations of infrastructure over annual rotations were based either on economic criteria (Boulard et al. 2011) or on occupation time criteria (Mila i Canals et al. 2008).

3.2 Data and methods for LCI

3.2.1 Type, origin, and quality of data

Across selected studies, type and origin of foreground data was of a wide diversity. Agricultural practices data were always presented as site-specific, i.e., representative for one vegetable product at the regional or the country scale. However, those data sets varied in time and space scales from national production data recorded for one or a few years to individual field data for a given crop cycle defined according to its location, its duration, and its position during the year. Data sources were also very variable; Boulard et al. (2011) and de Backer et al. (2009) used data from large-scale surveys carried out by agricultural development and extension services, while Abeliotis et al. (2013) and Mila i Canals et al. (2008) used data based on a restricted number of farms surveyed specifically for their study. Martínez-Blanco et al. (2009, 2010, 2011) and Romero-Gámez et al. (2012) used data from a 1 or 2-year trial, whose management followed regional recommendations. Torrellas et al. (2012) used a mix of data collected by local partners, producers, and sales cooperatives, as well as region-specific literature and data from experimental stations. Antón et al. (2005a) used a mix of data from a farmers' association for the soil cultivation scenario and from trials for the soilless scenarios. Background data was quite homogeneous among the panel of ten studies. Data regarding buildings, machinery, and inputs production were mainly based on literature or European and international databases. One exception was Martínez-Blanco et al. (2009) who provided site-specific data regarding compost production, based on data collected from a local compost plant.

3.2.2 Methods for field emissions

Table 1 shows the guidelines or references (columns 1 and 2) used by authors (last column) to estimate field emissions for various forms of reactive nitrogen (N_r). Most studies referred to recommendations from two general guidelines (Audsley et al. 1997; Nemecek and Kägi 2007) and one original paper (Brentrup et al. 2000), although transparency issues arose. Abeliotis et al. (2013) did not explicitly state whether they included the emissions from mineral fertilizers or not. Torrellas et al. (2012), Martínez-Blanco et al. (2011), and Martínez-Blanco et al. (2010) referred to several guidelines without specifying which one was used for each type of N_r emission.

Some adaptations were explicitly described such as the extension to organic fertilizers of the recommendation from Audsley et al. (1997) regarding nitrous oxide (N_2O) emissions (Mila i Canals et al. 2007, 2008). A few methods more specific to studied systems were also mentioned: Boulard et al. (2011) used publications specific to greenhouse

Table 1 LCI methods to estimate reactive nitrogen field emissions: guidelines and references, calculation method using emission factors and parameters, validity domain, and uses in selected studies

Guideline	References	Value, emission factors (EF)—parameters	Validity domain of the reference: Cropping system	Validity domain of the reference: Location	Uses in papers[a]
NH_3 emissions from mineral fertilizers					
Audsley et al. 1997; Nemecek and Kägi 2007	Asman 1992	*EF* % of $N_{fertilizer}$ Fertilizer type	Laboratory experiment	Europe	2, 4, 7, 9, 10[b] (1, 3, 5, 6)
Brentrup et al. 2000	ECETOC 1994	*EF* % of $N_{fertilizer}$ Fertilizer type Soil properties (pH, $CaCO_3$)	Mineral fertilizer	European Countries	8, (3, 5, 6)
NH_3 emissions from organic fertilizers					
Audsley et al. 1997	Menzi et al. 1998[b]	*EF=50%* of $N\text{-}NH_{4\ applied}$ $N\text{-}NH_{4\ manure}$	Cattle manure, Grassland	Switzerland	7, (5, 6)
Brentrup et al. 2000	Horlacher and Marschner 1990[b]	$N\text{-}NH_{4\ manure}$ Operation and incorporation date Infiltration rate Temperature, precipitation	Cattle slurry	Germany	8, 9, (5, 6)
Nemecek and Kägi 2007	Menzi et al. 1998[b]	$N\text{-}NH_{4\ manure}$ Fraction $_{area\ spread}$	Cattle manure, Grassland	Switzerland	1
N_2O emissions					
EPA 1995	Literature review	*EF* % of $N_{fertilizer}$ Fertilizer type	Fluid fertilizer	US	(11)
Audsley et al. 1997	Amstrong Brown et al. 1996[c]	*EF* % of $N_{fertilizer}$ Fertilizer type, Temperature	Granular fertilizer, wet soil	UK	2, 4, 9[e], 7, (3, 5, 6)
Brentrup et al. 2000	IPCC et al. 1997	*EF=1.25%* of $N_{fertilizer}$ minus NH_3 and NO_x losses	Mineral and organic fertilizer and manure	Global	8, 10, (3, 5, 6)
Nemecek and Kägi 2007	IPCC 2006[b]; Schmid et al. 2000[c]	*EF=1.25%* of N_{soil} , *EF=1.25%* of $N\text{-}NH_3$ losses, *EF=2.5%* of $N\text{-}NO_3$ losses, $N_{available\ fertilizers}$, $N_{crop\ residues}$, N_{fixed}	Mineral and organic fertilizer and manure	Global	(1)
NO_x emissions					
Audsley et al. 1997	No reference	*EF=10%* of $N\text{-}N_2O$ losses	*na*	*na*	2, 3, 4, 5, 6, 7, 9, 10
Nemecek and Kägi 2007	No reference	*EF=21%* of N_2O losses	*na*	*na*	(1)
N_2 emissions					
Brentrup et al. 2000	von Rheinbaben 1990[c]	*EF=9%* of N applied	Arable crop and grassland	Germany	2, 8
NO_3 emissions					
Audsley et al. 1997	Simmelsgaard 1998[e]	Reference leaching for recommended $N_{fertilizer}$ $N_{fertilizer}$	Arable crops and pastures, sandy and loamy soil	Denmark	2, 7, 10[b] (3[f] , 5, 6)
Brentrup et al. 2000	Own method	Soil texture, $NO_3\text{-}N_{soil}$ Precipitation	Crop production	Germany[d]	8, (3, 5 ,6)
Nemecek and Kägi 2007	Richner et al. 2006[c]	N_{uptake}, $N_{fertilizer}$ Fraction $_{N\ soil\ leachable}$ $N_{mineralized}$, Soil depth	Arable crops and meadow	Switzerland	(1)
	Cowell and Clift 1998	15 kg $N\text{-}NO_3.ha^{-1}$	*na*	*na*	9
	Sedilot et al. 2002	*EF=20%* (soil) and *48%* (substrate) of $N_{applied}$	Greenhouse	France	4

[a] Between brackets are uncertain uses (not specific information in papers), *Corresponding papers*: *1* Abeliotis et al. (2013), *2* Romero-Gámez et al. (2012), *3* Torrellas et al. (2012), *4* Boulard et al. (2011), *5* Martínez-Blanco et al. (2011), *6* Martínez-Blanco et al. (2010), *7* Martínez-Blanco et al. (2009), *8* de Backer et al. (2009), *9* Mila i Canals et al. (2007, 2008), *10* Antón et al. (2005a)

[b] Adaptation from the original method

[c] Reference not published in English

[d] Suggested value for parameters adapted to German climate

[e] Extended to organic nitrogen with 20 % of N as ammonium and 30 % as urea

[f] No nitrate leaching for recirculation irrigation systems; *na* information no data available

production systems to estimate nitrate (NO_3) emissions distinctly from open- and closed-loop systems, while Torrellas et al. (2012) deliberately omitted NO_3 emissions from systems involving a recirculation of drainage water.

The calculation of phosphorus (P) emissions was only detailed in four studies. Abeliotis et al. (2013) referred to recommendations from Nemecek and Kägi (2007), and de Backer et al. (2009) referred to Audsley et al. (1997). Boulard et al. (2011) and Mila i Canals et al. (2007, 2008) used data from specific publications, being, respectively, Sedilot et al. (2002) and Cowell and Clift (1998). Finally, Antón et al. (2005a) deliberately omitted PO_4 emissions on the basis that phosphorus was immobilized in the topsoil due to its high pH.

Regarding pesticides emissions, only three studies explicitly mentioned their inclusion in the inventory. Boulard et al. (2011) and Antón et al. (2005a) referred to the model from Hauschild (2000) adapted by Antón et al. (2004). De Backer et al. (2009) referred to the model from Birkved and Hauschild (2006).

Finally, only Mila i Canals et al. (2008) explicitly included CH_4 emissions from ammonium fertilizer application in the inventory.

3.3 Input flows and yields

Table 2 presents foreground data related to the field production stage for 72 cropping systems aggregated into 7 cropping system types presenting 7 product groups. For studies comparing systems according to different allocations rules, each system associated with a given allocation ratio was considered original and entered as an additional system.

3.3.1 Data completeness and reference flow

The completeness of field production data varied across studies. Data regarding energy consumption were not provided in four studies (Romero-Gámez et al. 2012; Martínez-Blanco et al. 2011, 2010, 2009). Torrellas et al. (2012) and Boulard et al. (2011) did not provide data on fuel consumption for field operations. Martínez-Blanco et al. (2009) did not provide specific data for water consumption.

Table 2 presents total fresh matter yields including commercialized and downgraded products. Those yields ranged from 2 t ha^{-1} for giant bean grown open-field in a Mediterranean context (Abeliotis et al. 2013) to 523 t ha^{-1} for tomato grown on substrate under heated greenhouse (Torrellas et al. 2012). Tomato showed yields above 100 t ha^{-1} while the other crops showed yield below 60 t ha^{-1}, regardless of the cropping system type.

3.3.2 Energy and input flows per ton of fresh matter yield

All cropping systems consumed diesel for field operations, except lettuce grown open-field in a tropical context (Mila i Canals et al. 2008). Diesel consumption ranged from 28 MJ t^{-1} for tomato grown under cold greenhouse on substrate (Antón et al. 2005a) to 1,237 MJ t^{-1} for giant bean grown open-field in a Mediterranean context (Abeliotis et al. 2013). Some systems were equipped with electrical pumps for irrigation leading to an electricity consumption from 5 MJ t^{-1} for tomato grown on soil under cold greenhouse (Antón et al. 2005a) to 301 MJ t^{-1} for giant bean grown open-field in a Mediterranean context (Abeliotis et al. 2013). This latter figure was due to its particularly low yield. Regarding greenhouse heating, the sources of energy were electricity, natural gas, or fuel, and in some cases included a cogeneration of electricity from fossil fuel leading to negative electricity consumption (Torrellas et al. 2012). The global energy consumption for heating varied from 23,970 MJ t^{-1} for tomato grown on substrate (Boulard et al. 2011) to 34,170 MJ t^{-1} for a similar system presented by Torrellas et al. (2012).

All cropping systems were irrigated, except leek (de Backer et al. 2009) and broccoli grown open-field in a temperate context (Mila i Canals et al. 2008). The water volumes applied ranged from 1 m^3 t^{-1} for lettuce grown open-field in a tropical context (Mila i Canals et al. 2008) to 1,570 m^3 t^{-1} for giant bean grown open-field in a Mediterranean context (Abeliotis et al. 2013). However, 80 % of systems showed water volumes below 100 m^3 t^{-1}. Systems showing the highest water consumption per ton were giant bean, green bean, and broccoli grown open-field in Mediterranean context with very low crop yields.

All cropping systems received synthetic fertilizers, except for the lettuce in open-field cropping systems in Uganda (Mila i Canals et al. 2008). Variations of fertilizer inputs across systems were lower than variations for other inputs. Nitrogen rates ranged from 1 kg t^{-1} for lettuce grown open-field in a tropical context (Mila i Canals et al. 2008) to 19 kg t^{-1} for broccoli grown open-field in a Mediterranean context (Mila i Canals et al. 2008). Cauliflower and tomato grown open-field in Spain (Martínez-Blanco et al. 2010; Martínez-Blanco et al. 2009; Martínez-Blanco et al. 2011) and green bean and leek grown open-field in UK and Belgium (Mila i Canals et al. 2008; de Backer et al. 2009) did not receive any phosphate-based synthetic fertilizers. Phosphate rates reached 29 kg t^{-1} for green bean grown open-field in a Mediterranean context (Romero-Gámez et al. 2012). Applications of organic fertilizers were not systematic and never occurred for heated greenhouse types and types on substrate. The types and input rates of organic fertilizers were systematically described. However, the nutrient contents of the organic fertilizers were not homogeneously reported in the studies. Organic fertilizers rates reached 4 t t^{-1} for giant bean grown open-field in a Mediterranean context (Abeliotis et al. 2013).

3.4 LCIA results

Figure 1 presents LCIA results expressed per kilogram of fresh matter yield for the three impact categories selected

Table 2 Inputs flows for the field production stage expressed per ton of fresh yield and fresh yield for the 72 systems aggregated by cropping system type, product group, and reference

Cropping system type	Product group	Reviewed paper	CS[a]	Fresh yield[b]	Energy			Water	Synthetic fertilizers		Organic fertilizers
					Electricity	Gaz/Fuel	Diesel		Nitrogen	Phosphate	
				t ha^{-1}	MJ t^{-1}	MJ t^{-1}	MJ t^{-1}	m^3 t^{-1}	kg N t^{-1}	kg P_2O_5t^{-1}	t t^{-1}
GH-Heat-Sub	Tomato	Torrellas et al. 2012	4	523	−2835	37026	na	14	4	2	0
		Boulard et al. 2011	8	440	0	23970	na	29	6	3	0
GH-Heat-soil	Lettuce	Mila i Canals et al. 2008	2	58	1153	27498	46	7	1	1	0
GH-Cold-Sub	Tomato	Torrellas et al. 2012	1	165	0	0	na	29	5	3	0
		Antón et al. 2005a, b	2	150	5	0	28	24	5	6	0
GH-Cold-Soil	Green bean	Romero-Gámez et al. 2012	4	55	na	na	na	88	1	7	0
	Tomato	Boulard et al. 2011	1	150	0	0	na	33	3	2	0
		Martínez-Blanco et al. 2011	3	161	na	na	na	33	2	0	0
		Antón et al. 2005a, b	1	120	5	0	35	29	6	3	0
OF-Temp	Green bean	Mila i Canals et al. 2008	2	12	0	0	265	42	10	0	0
	Broccoli	Mila i Canals et al. 2008	4	12	0	0	486	0	14	3	0
	Leek	de Backer et al. 2009	2	33	0	0	156	0	1	0	1
	Lettuce	Mila i Canals et al. 2008	6	22	0	0	742	37	6	1	0
OF-Med	Giant Bean	Abeliotis et al. 2013	7	2	301	0	1237	1570	10	20	4
	Green bean	Romero-Gámez et al. 2012	2	19	na	na	na	265	4	29	0
	Broccoli	Mila i Canals et al. 2008	4	16	0	0	521	140	19	5	0
	Cauliflower	Martínez-Blanco et al. 2010	3	57	na	na	na	41	3	0	0
	Lettuce	Mila i Canals et al. 2008	4	36	0	0	211	54	10	5	1
	Tomato	Martínez-Blanco et al. 2009	6	124	na	na	na	na	3	0	0
		Martínez-Blanco et al. 2011	3	127	na	na	na	45	3	0	0
OF-Trop	Green bean	Mila i Canals et al. 2008	2	24	0	0	42	36	1	1	1
	Lettuce	Mila i Canals et al. 2008	1	41	0	0	0	1	0	0	0

GH greenhouse, *OF* open-field, *Temp* temperate climate, *Med* Mediterranean climate, *Trop* tropical climate, *na* data were not available in the published documents

[a] Number of cropping systems aggregated within the line

[b] Fresh yield expressed in t ha^{-1} for one crop cycle, including downgraded products

(global warming, acidification, and eutrophication potentials) for the 72 cropping systems of the 10 reviewed studies. The 72 cropping systems were successively grouped by cropping system type, product group, and reviewed paper. When LCIA results were expressed using functional units involving quality aspects, necessary conversions were used to homogenize the functional unit to yields presented in Table 2. LCIA results expressed per square meter and crop cycle are given in Electronic Supplementary Material 1.

3.4.1 Global warming potential

The cropping system types under heated greenhouse, GH-Heat-Sub and GH-Heat-Soil, had a greater global warming potential (GWP) than other types, at 2.03 and 2.12 kg CO_2-eq. per kilogram of fresh yield, respectively (Fig. 1). GWP variations across GH-Heat-Sub systems were mostly due to differences in the origin of the energy. Indeed, GWP from GH-Heat-Sub systems presented by Torrellas et al. (2012) showed important variations (±58 %) mainly due to energy sources and associated allocations and substitution rules (gas=5.00 kg CO_2-eq kg^{-1} fresh yield; cogeneration + allocation=2.00 kg CO_2-eq kg^{-1} fresh yield; cogeneration + avoided burdens= 0.78 kg CO_2-eq kg^{-1} fresh yield; geothermal=0.44 kg CO_2-eq kg^{-1} fresh yield). GWP variations across the GH-Heat-Soil systems were due to different energy consumptions for greenhouse heating. According to authors presenting the two lettuce cropping systems (Mila i Canals et al. 2008), one farm grew only one cycle of lettuce indoors, very likely during the coldest period, while the other farm grew lettuce indoors all year round, with on average five cycles per year. The variation in energy consumption between systems of the GH-Heat-Soil type could result from the crop cycle position within the year. GWP per kilogram fresh yield for all other types ranged from 0.05 (OF-Trop) to 0.45 kg CO_2-eq. (GH-Cold-Soil) without showing clear differences due to large intratype variations. For

example, the higher impact of green bean under cold greenhouse results from the misting system used to cool down the greenhouse temperature.

Products groups showed undifferentiated GWP values (Fig. 1), ranging from −0.36 (Broccoli) to 0.89 kg CO_2-eq kg^{-1} fresh yield (Tomato). Negative GWP was observed in the articles by Martínez-Blanco et al. (2009, 2010, 2011) due to the avoided dumping of organic wastes in systems using compost as a fertilizer. For example, the tomato system with compost only (Martínez-Blanco et al. 2009) showed a GWP of 0.15 kg CO_2-eq kg^{-1} fresh yield without considering avoided burdens and −0.90 kg CO_2-eq kg^{-1} fresh yield with avoided burdens.

While being similar per kilogram fresh yield, the GWP for GH-Heat-Soil and GH-Heat-Sub systems were significantly different per unit of area (Electronic Supplementary Material 1), the lowest being for the GH-Heat-Soil type. Such discrepancy between impacts expressed by the two functional units resulted from the combined effect of yield per day and crop duration; the lettuce being grown for 2 to 3 months only while tomato were grown for up to 11 months. Moreover, while showing undifferentiated values between product groups per kilogram fresh yield, the GWP per unit of area for the tomato group clearly exceeded the GWP of other product groups. The sensitivity of results to the FU choice highlighted here the high intensity of management (quantity of infrastructure and energy used per area) for tomato system grown under heated greenhouse.

3.4.2 Acidification

Regarding the acidification potential (AP), expressed in grams of SO_2 equivalent per kilogram of fresh yield, cropping system types did not present clearly different means due to large variations within types and products groups. However, we could relate the ranking of impact between product groups to the fertilizer efficiency, i.e., the ratio of fertilizers inputs per kilogram of fresh yield (as shown in Table 2). The giant bean group (Abeliotis et al. 2013), presenting the lowest manure efficiency (4 t t^{-1} fresh yield) as well as a low mineral nitrogen efficiency (10 kg N t^{-1} fresh yield), had the largest impact with an average of 11.26 g SO_2-eq per kg of fresh yield. The authors of this study identified field emissions from sheep manure as the major contributor for AP. The second greater impact (3.26 g SO_2-eq kg^{-1} fresh yield) was shown by the broccoli group, which showed the lowest mineral nitrogen efficiency (19 kg N t^{-1} fresh yield). The particularly low yields shown by these two groups suggested that AP variations were greatly affected by yields. The lowest impact (0.42 g SO_2-eq kg^{-1} fresh yield) was shown by the leek group, presenting one of the highest mineral nitrogen efficiency (1 kg N t^{-1} fresh yield).

The field emissions and low yields of giant bean and broccoli contributed largely to the high AP of the Mediterranean open-field systems type, averaging 4.28 g SO_2-eq kg^{-1} fresh yield. However, this mean was associated with a particularly large coefficient of variation (±72 %) stemming from broad variations of input efficiency across systems within this type.

Variations of AP per unit of area (Electronic Supplementary Material 1) regardless of aggregation mode were greater than variations for AP per kilogram of vegetable (±156 vs. ±71 %). Such differences between results expressed by the two functional units highlighted the yield effect, as already suggested previously. The variations of AP between cropping system types and product groups were reduced per kilogram fresh yield by integrating an aspect of input efficiency, as yields are supposed to be correlated to inputs of systems. Similarly to GWP, the ranking of impact per unit of area for product groups and cropping system types differed from the ranking using the functional unit per kilogram of fresh yield. Indeed, AP expressed per unit of area for tomato systems clearly exceeded the AP of other products groups. Similarly, AP expressed per unit of area for GH-Heat-Soil systems clearly exceeded the AP of other cropping systems types. Again, the sensitivity of results to the FU choice highlighted the high intensity of fertilization management (quantity of fertilizer per unit of area) for tomato systems grown under heated greenhouse.

3.4.3 Eutrophication

Regarding the eutrophication potential (EP) expressed in grams of PO_4^{3-} equivalent, giant bean systems showed a greater impact (1.75 g PO_4^{3-}-eq kg^{-1} fresh yield) than other products groups. Broccoli and green bean systems also showed a high impact (1.01 and 0.95 g PO_4^{3-}-eq kg^{-1} fresh yield, respectively). For broccoli systems, such high impact mainly resulted from low mineral nitrogen efficiency, while for green bean, it resulted from low mineral phosphorus efficiency (29 kg $P_2O_5 t^{-1}$ fresh yield). For giant bean, the high impact resulted from both low phosphorus and nitrogen efficiencies (10 kg N and 20 kg $P_2O_5 t^{-1}$ fresh yield, respectively). We can notice that despite being a leguminous crop (i.e., fixing nitrogen from the atmosphere), the giant bean group presented relatively high nitrogen inputs contributing to its high EP. The cauliflower group showed less impact than other groups (−1.53 g PO_4^{3-}-eq kg^{-1} fresh yield) due to the absence of phosphorus inputs, the high mineral nitrogen efficiency (3 kg N t^{-1} fresh yield), and the system expansion rules used by Martinez-Blanco et al. As already explained for GWP, the latter obtained a negative EP thanks to negative nitrogen and phosphorous emissions from avoided organic waste dumping in the system using compost as a fertilizer. Despite low fertilizer rates, the leek group showed the third greater

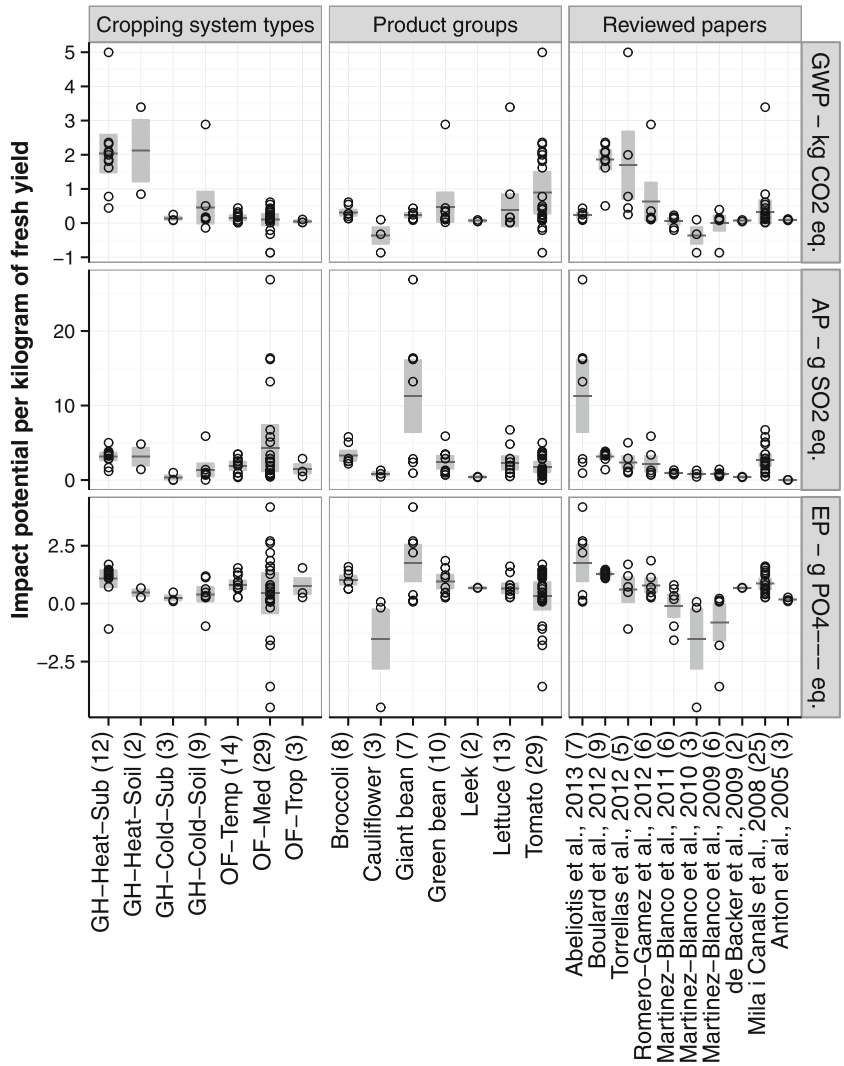

Fig. 1 Global warming potential (*GWP*), acidification potential (*AP*), and eutrophication potential (*EP*) expressed per kilogram of fresh yield from cradle-to-harvest for the 72 systems aggregated per cropping system type, product group, and reviewed paper. *Figures* between brackets correspond to the number of systems in the group. *Gray boxes* correspond to error bars centered on the mean of the group (*dark gray dash*)

impact (0.68 g PO_4^{3-}-eq kg^{-1} fresh yield) due to important phosphorus emissions.

System expansion related to compost fertilization contributed largely to artificially reduce the average EP of Mediterranean open-field cropping systems (only 0.45 g PO_4^{3-}-eq kg^{-1} fresh yield despite the high impact of giant beans) which presented the highest standard error (211 %) across all types, products, and impact categories. Across all types, GH-Heat-Sub showed the greatest EP (1.08 g PO_4^{3-}-eq kg^{-1} fresh yield). This greatest impact occurred despite the avoided electricity production thanks to the use of natural gas for cogeneration assumed by Torrellas et al. (2012). Over the 12 GH-Heat-Sub systems, 1 system presented in Torrelas et al. (2012) and 20 % of systems from Boulard et al. (2011) were closed-loop.

Similarly to AP, the ranking of impact per unit of area for product groups and cropping system types differed from the ranking of impacts per kilogram of fresh yield: the EP per unit of area of GH-Heat-Soil systems exceeded the EP of other cropping systems types, including GH-Heat-Sub and the EP per unit of area of tomato systems exceeded the EP of other products groups. This latter result highlighted once again the high intensity of fertilization management per area for tomato system grown under heated greenhouse.

4 Relevance of the typology to compare LCIA results from a diversity of cropping systems and vegetable products

While it is difficult to thoroughly analyze LCIA results from several individual studies, using a typology allowed us to provide general conclusions on the environmental impacts of vegetable products and to identify the main cropping systems components responsible for these impacts.

For GWP, we can conclude that the aggregation per cropping system type was the most relevant with heated greenhouse types showing the greatest impact. In agreement

with several studies dealing with fruit and vegetable products (Stoessel et al. 2012; Hospido et al. 2009), we identified the type of energy consumed for greenhouse heating as an important source of impact variations. However, GWP for cold greenhouse and open-field types could not be distinguished due to low contribution of infrastructures compared to the impact associated to material and input uses. Our analysis also showed that the crop position within the year led to important GWP variations particularly due to the requirement or not for heating. For AP, our analysis suggested that the aggregation per product group was the most comprehensible with the giant bean group showing the greatest impact and the leek group showing the lowest impact. For AP and EP, we identified phosphorus and nitrogen emissions from both mineral and organic fertilizers as the major contributors to the impacts. However, our analysis identified system expansion rules as another important source of variations resulting in the cauliflower group showing the lowest impact. Finally, comparing two distinct functional units, we showed that LCIA results per kilogram of fresh yield was largely affected by input efficiency per mass of product, while LCIA results per area were largely affected by management intensity per area. This discrepancy led to a change on the ranking of cropping system types and product groups according to the functional unit.

Despite those important insights, the benefits of the typology were hampered by the occurrence of (1) low variations between cropping system types and products and (2) high variations within types and products.

We explored several hypotheses to explain these variations.

1. Inherent variability of cropping systems and products
2. Discrepancies and relevance of methodological choices
3. Limitations in our typology approach

We further elaborate on these three potential sources of limitations in Sections 4.1, 4.2, and 4.3 with a special focus on the methods used for the estimation of N_r emissions in Section 4.4.

4.1 Inherent variability of cropping systems and representativeness issues

Some variations within cropping system types can be explained by the actual variability attached to cropping systems and products in general. Indeed, the variability of farmer's practices, soil, and climate conditions affects cropping systems performances. However, across studies, the poor or unspecified data representativeness reduced the possibilities to identify and interpret this inherent variability.

Across studies, technological, geographical, and time-related representativeness of data regarding goal and scope were difficult to assess. Most studies provided detailed information on techniques involved in the field production stage as they were often an object of comparison between systems. However, the time and geographical scales were less detailed. We could locate the data used in time and space but their representativeness regarding the studied region and period was poorly addressed. Only Boulard et al. (2011) provided figures on national production and discussed the representativeness of the data used for the LCA. Abeliotis et al. (2013) tried to address the intrafarms variability proposing a weighted mean resulting from an area-based aggregation of different farms, but did not provide standard deviations. Several LCA studies dealing with vegetable crops (Cellura et al. 2012a) and other crops (Mouron et al. 2006) showed the influence of the management on the environmental performances of systems which pleads for a better inclusion of farms variability in LCA studies.

4.2 Discrepancies in methodological choices

4.2.1 System boundaries and completeness of studies

We highlighted a lack of homogeneity regarding system boundaries and cutoff rules. Authors listed and justified most of excluded processes following recommendations from the ILCD handbook (European Commission 2010). However, the constraint of reporting an LCA through a publication often led to a lack of transparency regarding included processes. In addition, several exclusions were not relevant with regard to their potential contribution to the environmental impact of vegetable products.

First, some important stages were not systematically included. *The waste treatment stage* was excluded from three studies over the ten reviewed, although Antón et al. (2005b) showed that it contributed for 20 to 94 % of GWP and 5 to 50 % of EP for tomato production, depending on the type of management considered. Our review did not allow identifying neither the diversity of waste management techniques nor associated impact variations across systems. *The nursery stage* was not explicitly included in six studies. To our knowledge, there is no literature providing LCIA results for the nursery stage of vegetable. However, for tomato production under cold greenhouse, Boulard et al. (2011) identified heating during the nursery stage as the major contributor for GWP of the whole system.

Second, phosphorus emissions were not included in five studies with systems fertilized with mineral or organic phosphorus. One of these studies explained that phosphorus was immobilized due to high soil pH resulting in no losses by leaching. However, phosphorus losses occur as soluble phosphate through leaching and run-off but also through the erosion of soil particles. Boulard et al. (2011) showed that phosphate in soil and water contributed from 45 % for heated greenhouse on substrate to 63 % for cold greenhouse on soil to the eutrophication potential at farm-gate. Due to the

heterogeneous description of drainage water management in reviewed papers, we could not analyze eutrophication potential variations related to this aspect. However, Boulard et al. (2011) also stated that the phosphorus emission could probably be reduced by 40 % when switching from an open-loop system to a closed-loop system.

Finally, the impacts of pesticide use could not be compared across studies since six of them did not assess human or ecosystem toxicities. According to the ILCD handbook (European Commission 2010), all impact categories that are relevant for the LCIA study shall be included. Several studies showed that pesticide use dominated the life-cycle toxicity impact of vegetable production (Antón et al. 2004; Margni et al. 2002). Among those papers which included human and ecosystem toxicity impact categories, two did not explicitly include pesticides emissions in the field. Mila i Canals et al. (2008) criticized current estimation methods for being either too simplistic (Audsley et al. 1997) or too impractical (Birkved and Hauschild 2006), and proposed an additional indicator based on pesticide use.

4.2.2 Transparency and relevance of methods for field emissions

Readers should have the capacity to interpret the contribution of field emissions to the environmental impacts. However, the references used to estimate these fluxes were not sufficiently detailed, neither were the parameters values used for calculation. Four papers did not report the methodology used to estimate each emission from fertilizer and pesticide use. In addition, authors did not detail the parameter values used for the calculations, preventing the reader from recalculating emissions when they were not included in the article. The acidification potential and the eutrophication potential should be largely affected by reactive nitrogen-based and phosphorus-based field emissions. Unlike Boulard et al. (2011) and Antón et al. (2005a), our review did not identify a reduction of the eutrophication potential between systems on substrate and systems on soil, regardless of the functional unit used. In addition, we could not properly identify the respective contributions of phosphorus and nitrogen emissions to the eutrophication potential. Considering the particularly weak description of methods to estimate phosphorus emissions and the lack of consensus, we can assume that important EP variations were related to methodological choices.

Detailed information on the estimation methods would have permitted to explain why those systems so diverse a priori showed similar impacts for AP and EP and to assess the relevance of the methods used. This is especially likely for waterborne emissions (the main contributors to EP), since differences in climate, irrigation, fertilizer managements, and growing media result in particular water and nutrients dynamics. Since N_r emissions were systematically included in inventories and often responsible for significant acidification and eutrophication potential impacts, a special focus on their estimation methods is proposed in Section 4.4.

4.3 Weaknesses in reporting, a limitation to our typology approach

Our typology was an a priori typology based on a restricted number of characteristics of vegetable cropping systems. A quantitative typology based on a statistical approach (principal component analysis and hierarchical clustering) would have been preferable. However, it was not feasible in our situation given the lack of transparency in the reporting of key cropping systems characteristics across studies. Below, we identify often missing although critical parameters to be included and reported in LCA studies for vegetable products. These parameters could allow improving the relevance of further attempts at characterizing the variability of LCIA results across vegetable products. Such characterization based on a meta-analysis should therefore provide information about important influencing factors for the environmental performances of vegetable products for the attention of policy makers, food industries, consumers, and producers.

Our analysis showed that the crop position within the year led to important GWP variations. For some vegetable crops, several cropping cycles can occur on the same field during 1 year. Cellura et al. (2012a) showed that crop rotations can lead to a clear reduction of all environmental impacts for both tomato and melon, especially with respect to waste production and allocation rules.

Our analysis also showed the important contribution of organic fertilizers to AP and EP. However, information regarding the types and composition of organic fertilizers was not homogeneous across studies. The type and the composition of the organic fertilizers inform not only on the nutrient inputs to cropping systems, but also on the environmental risks associated to their application. Indeed, in addition to nitrogen and phosphorus contents, compost (Weber et al. 2007; Shiralipour et al. 1992) and manures are known to be sources of a diversity of trace contaminants such as heavy metals and persistent organic pollutants. Finally, the method of application plays an important role regarding the acidification and eutrophication potentials with some application techniques of manure especially designed to abate ammonia emissions (Langevin et al. 2010).

Finally, irrigation practices appeared in recent studies in Mediterranean areas as an important contributor for GWP and water consumption (Abeliotis et al. 2013; Cellura et al. 2012a, b; Romero-Gámez et al. 2012). Our analysis did not allow identifying the contribution of irrigation practices to the impact of vegetable production due to heterogeneous description of energy and water consumed. However, the huge diversity of irrigation practices from recirculation systems to sprinkler

irrigation systems should have affected the environmental performances of vegetable production systems.

4.4 Relevance and validity of the methods used for the estimation of reactive nitrogen emissions

Field emissions are substances emitted during the field production stage. Emissions can be either directly caused by an input application (fertilizers or pesticides) or by processes occurring in the soil and in the atmosphere (nitrogen deposition, drainage, and soil mineralization). Field emissions do not include emissions from fuel burned in tractors. In this section, we focused on reactive nitrogen (N_r) emissions because they were systematically included in inventories and often responsible for significant acidification and eutrophication potential impacts. In Table 1, the references detailing calculation methods were analyzed regarding the parameters included and the validity domain of the specific method, be it an emission factor or a more complex equation. In the next subsections, an in-depth analysis for each emission process is proposed regarding the adequacy of each reference to the specific conditions of the diverse vegetable cropping system types. Recommendations are made in the last section of this paper.

4.4.1 Volatilization of applied fertilizers and associated ammonia emissions

Volatilization is a physicochemical process leading to ammonia (NH_3) emissions, which have high acidifying properties. In the three guidelines used, NH_3 emissions from mineral and organic fertilizers were dealt with separately.

For mineral fertilizers, the guidelines of Audsley et al. (1997) and Nemecek and Kägi (2007) recommended emission factors from Asman (1992). This reference proposed emission factors measured under controlled conditions in the laboratory for each type of fertilizer used in Europe. These emission factors were used as references for the whole Europe, until the publication of the ECETOC report (1994) recommended by Brentrup et al. (2000). ECETOC (1994) recommended a new set of emission factors based on an extensive literature review, depending on the country considered and the occurrence of soils with a pH greater than 7 (indicative of calcareous soils).

For NH_3 emissions from organic fertilizers, the guidelines from Audsley et al. (1997) and Nemecek and Kägi (2007) recommended a calculation method developed by Menzi et al. (1998). This method was based on experiments in Switzerland, where liquid manure was applied to grassland. Audsley et al. (1997) suggested simplified emission factors depending on the ammonia content of the organic fertilizer. By contrast, Nemecek and Kägi (2007) slightly adapted the empirical equation from Menzi et al. (1998) with parameters related to techniques of application. Finally, Brentrup et al. (2000) recommended an empirical equation developed by Horlacher and Marschner (1990) in a temperate context for cattle slurry spread on arable crops. Some parameters of this empirical equation may be adjusted to account for different soils, crops, and times of application with regard to incorporation or precipitation.

None of those references are actually suitable to estimate emissions from open-field systems under Mediterranean or tropical climates since high temperatures may entail large variations in the emissions, especially if the fertilizer application occurred in the hottest season. For greenhouse systems, the use of those calculation methods was very remote from their validity domain as wind speed and temperature effects were not included, not to mention the effect of plastic mulch. Ammonia emissions are largely variable according to crop type, local context, and application techniques (Bussink and Oenema 1998; Langevin et al. 2010).

4.4.2 Denitrification of soil nitrogen and associated gaseous emissions

Nitrification and denitrification of soil nitrogen are responsible for the emission of nitrous oxide (N_2O), nitrogen oxides (NO_x), and nitrogen gas (N_2) emissions. N_2O is a potent greenhouse gas, while NO_x contributes mainly to photochemical oxidant formation and terrestrial acidification. In the two guidelines (Audsley et al. 1997; Nemecek and Kägi 2007) and the original paper from Brentrup et al. (2000), each emission is dealt with separately.

For N_2O emissions, Audsley et al. (1997) associated N_2O emissions to nitrogen from fertilizer application and emission factors were based on an unpublished reference. These emission factors depended on the fertilizer type and the soil temperature and belonged to the range (0.4–3 %) (as a fraction of applied N). Later on, the guidelines from Brentrup et al. (2000) and Nemecek and Kägi (2007) recommended emission factors from (IPCC et al. 1997), based on an extended review of published field experiments mainly from temperate regions. Brentrup et al. (2000) recommended using the direct emission factor from the IPCC methodology. The direct emission factor corresponds to the proportion of soil nitrogen turnover emitted as N_2O, including N mineralized from mineral and organic fertilizer N inputs, N fixation from legumes, and N in plant residues. In addition to the emission factor for direct emissions, Nemecek and Kägi (2007) also included the two indirect emission factors from IPCC et al. (1997) via the equation developed by Schmid et al. (2000). The indirect emission factors correspond, respectively, to the fraction of N inputs volatilized as ammonia, which is further deposited to soils and emitted as N_2O and, the fraction of N inputs leached as nitrates and further emitted as N_2O.

Only two guidelines included the estimation of NO_x emissions. Brentrup et al. (2000) neglected this emission, probably because there was no consensus on its emission factor. The guidelines from Audsley et al. (1997) and Nemecek and Kägi (2007) agreed on NO_x emissions equal to 21 % N_2O emissions. None of them quoted any published reference to justify such figure, which is actually contradicted by recent literature (Stehfest and Bouwman 2006). Finally, although not of environmental relevance, N_2 emissions were included by Brentrup et al. (2000) in their nitrogen balance approach to infer nitrate leaching. They proposed a constant emission factor of 9 % of the nitrogen applied according to von Rheinbaben (1990).

Providing a unique emission factor, the IPCC guidelines (tier 1) do not allow for discriminating between systems but for calculating the soil nitrogen input. Nevertheless, the broad validity domain of this reference and its wide use make it the most appropriate method currently available for open-field systems, even under tropical conditions as a few field experiments used to calculate the emission factors were led in tropical areas. However, its use for greenhouse systems was far beyond the scope of the IPCC report. It does not appear that significant improvements can be possible using a unique emission factor, since many parameters influencing N_2O and NO_x emissions were recently evidenced and their interactions are not fully understood (Stehfest and Bouwman 2006). The effect of temperature and fertilization on soil nitrogen content and soil pH and the effect of the irrigation on soil humidity are particularly relevant to consider for vegetable cropping systems.

4.4.3 Leaching and associated nitrate emissions

Nitrate leaching occurs when there is an accumulation of NO_3 in the soil profile that coincides with or is followed by a period of drainage. Therefore, excessive nitrogen fertilizer or N applications before drainage events, plowing, or long fallow without cover can all potentially lead to NO_3 leaching losses. In each guideline analyzed, a specific approach for nitrate leaching estimate is recommended in relation to the specific context where the method was developed.

Audsley et al. (1997) recommended the use of a Danish approach adapted from a statistical equation from Simmelsgaard and Djurhuus (1998). In this approach, a reference leaching loss for a recommended fertilizer rate was used as a parameter to reflect the soil capacity for leaching. The validity domain of this statistical model is restricted to Danish conditions where references are available regarding the reference leaching. Brentrup et al. (2000) suggested the use of a conceptual model based on a nitrogen balance coupled with an empirical equation reflecting drainage events. Although following a more conceptual approach, this equation was calibrated under German conditions for arable crops only. Finally, Nemecek and Kägi (2007) recommended the use of a conceptual approach including a set of emission factors. These emission factors were calculated using a mechanistic model developed by Richner et al. (2006), but were further calibrated under Swiss conditions for arable crops. This conceptual approach included parameters related to soil, plant uptake, soil coverage, and risk of nitrogen leaching depending on the crop types and the months in which fertilizers were applied. This range of parameters allowed the user to adapt the calculation within the range of situations defined in the method (arable crops under temperate climate).

The current methods used to estimate nitrate emissions were more complete in terms of driving parameters compared to other emissions, but remained mostly valid for arable crops in temperate contexts. Overall, the only reviewed study using a suitable method for the estimation of leaching was de Backer et al. (2009) who assessed leek cropping systems (without irrigation) under temperate climate using the Brentrup's method (2000). Otherwise, none of these methods were really suitable for estimating nitrate leaching for any other vegetable cropping systems.

5 Conclusions and recommendations

This paper reported on the current practice for the LCA of vegetable products with a focus on the field production stage. It was a first attempt at comparing potential impacts of a large range of cropping systems representative of the current European supply mix of vegetable products. It presented aggregated LCIA results (1) according to the cropping system type through an original typology, (2) according to the product group, and (3) according to the reference. Setting a typology of systems appeared as a suitable approach that should be generalized to characterize systems diversity and obtain representative life-cycle inventory (LCI) data, in relation to the function and scale defined in the goal and scope. We can conclude that the heated greenhouse system types showed the greatest GWP impact due to the crop position within the year in relation to energy requirement for heating. When GWP was expressed per area, the tomato group showed the highest impact due to high management intensity per unit of area. Regarding AP and EP, the giant bean group showed the greatest impact due to low yields, responsible for low input efficiency. When AP and EP were expressed per unit of area, the tomato group showed the greatest impact due to high fertilizer management intensity per area.

We highlighted important sources of impact variations across systems. Important GWP and EP variations were caused by system expansion rules related to energy and compost used. Important GWP variations were due to the crop position within the year and the crop duration, in relation to energy requirement for heating. Important AP and EP

variations were caused by yield variations and diverse fertilization managements.

However, the ability to compare the environmental impact for these diverse field production stages was hampered by (1) weaknesses regarding transparency of goal and scope, (2) a lack of representativeness and completeness of data used for the field stage, and (3) heterogeneous and inadequate methods for estimating on field emissions across reviewed studies.

Generally speaking, several aspects would deserve a systematic inclusion and a dedicated reporting in the LCA of vegetable products. First, human and ecosystem toxicity impacts should be more systematically assessed to consider pesticide practices, as well as the impact of freshwater use to account for the frequent use of irrigation and the location of systems often in contexts of water stress. Their absence can be partly explained by the lack of a consensual method at the time of their publication regarding both methods for estimating emissions (for pesticides) and for characterization. For these categories, there is an urgent need for further investigation. Second, geographical and time-scale representativeness should be better addressed with regard to inventory data for the field production stage of vegetable products. In agreement with the ILCD handbook (European Commission 2010), we strongly recommend providing data describing the sample of farms surveyed with regard to its representativeness in connection with the scope of the LCA. Variability of the management between farms and years should be better accounted for through valid sampling procedures and discussed in the interpretation step, based on consensual quality criteria such as the data quality criteria proposed by Weidema and Wesnæs (1996). Finally, the waste treatment and the nursery stage should be systematically included in inventories with detailed information about techniques involved, inputs, and energy consumption and emissions at least until their insignificant contribution would be clearly demonstrated.

More specifically, an effort should be made to collect and report accurate, precise, and complete inventory data regarding the main discriminating characteristics of cropping systems representative for the studied function. Authors should more often take opportunities offered by many journals to provide full inventories in supplementary materials. A quality reporting of key cropping systems' data would allow better quality meta-analyses including statistical analysis as an extension of the analysis proposed in this paper. Table 3 summarized those key parameters to be included in inventories according to cropping system specificities. In agreement with recommendations from several authors of LCA for vegetable products (de Backer et al. 2009; Andersson et al. 1998), land occupation characteristics (the crop duration, its position within the year, the previous and following crops, and crop residues management) along with detailed allocation rules should be described to properly assess the impact of vegetable crops on a yearly-basis. As proposed by several authors, another solution could be to expand the system to the complete rotation. The organic fertilizer management should be thoroughly taken into account for open-field cropping systems, in particular regarding the allocation rules related to its use. There is also a pressing need to investigate impacts related to the contaminants contained in organic fertilizers. Being an important source of nutrients especially regarding integrated and organic production orientations, more detailed data on organic fertilization is deemed necessary. Finally, regarding irrigation practices, the infrastructure and energy consumption should be better documented with regard to its potential contribution to global warming. There is also a pressing need to specify volumes and origin of the water used especially in a context where water is a scarce resource. The irrigation infrastructure (drip or sprinkler), the quantities and nature of energy used (diesel or electricity), and the quantities and origin of water used (river, groundwater) should be systematically detailed in LCA dealing with vegetable products.

Regarding field emissions, we recommend to systematically estimate emissions of phosphorus and pesticides in line with the specificities of the cropping systems evaluated and to report on the methods used for their estimation. Regarding nitrogen reactive emissions, we examined the relevance of the methods used to the diversity of cropping systems studied. Table 3 summarizes identified gaps in terms of methods availability and provides recommendations on the best available methods according to cropping system specificities. We believe that available methods could not allow a proper estimation of N_r emissions for all cropping systems, due to the diversity of vegetable systems. For gaseous emissions from systems under greenhouse, there is currently no available method accounting for such confined atmospheres (radiation, humidity, and wind), plastic mulching or substrate conditions. Conversely, for open-field systems, we can recommend the use of ammonia emission factors from ECETOC (1994) for mineral fertilizers. For ammonia emissions from organic fertilizers, the method proposed by Brentrup et al. (2000) has the advantage to allow the parameterization of soil type and plant cover. For ammonia emissions under tropical climate, the emission factors proposed by Bouwman and Van Der Hoek (1997) seem the most appropriate, and ECETOC (1994) group III can be used as a complement for fertilizers not dealt with in the article. For nitrous oxide emissions, direct and indirect emission factors proposed by IPCC (2006) seem the most appropriate. For both ammonia and nitrous oxide emissions, further developments are required to calibrate more mechanistic tools easily transposable in Mediterranean and tropical contexts. These tools should at least include parameters to account for temperature, soil type, and application techniques. For the estimation of nitrate leaching, we can recommend the use of the nitrogen balance proposed by Brentrup et al. (2000). However, a proper water balance should be done, accounting for the soil and climate specificities in Mediterranean or

Table 3 Summary of recommendations related to key parameters to be included in LCI and methods to be used for the estimation of reactive nitrogen (N_r) emissions to account for specificities of vegetable cropping systems

Specificities of cropping systems	Key parameters	Methods for the estimation of N_r emissions			
		NH_3 mineral fertilizers	NH_4 organic fertilizers	N_2O and NO_x	NO_3
Vegetable cropping systems	• Fresh matter yield and commercial yield if suitable • Nitrogen and phosphorus inputs along with fertilizer types • Water inputs and origin • Irrigation system specificities • Crop duration and position within the year • Previous and following crop • Crop residue management	×	×	×	×
1. Greenhouse systems	• Greenhouse materials and associated waste management • Allocation rules for infrastructures	ø	ø	ø	Brentrup et al. (2000) adapted to soil type and irrigation management
1.1. Heated greenhouse systems	• Energy inputs and origin • Allocation and substitution rules associated to co-generation				
1.2. Systems with substrate	• Substrate type and associated waste management • Drainage water management	ø		ø	Bres (2009)
2. Open-field systems	• Soil type • Rainfall • Origin and composition of organic fertilizers • Allocation rules associated to organic fertilizers	ECETOC (1994)…	Brentrup et al. (2000) parameterized for…	IPCC (2006) and Nemecek and Kägi (2007)	IPCC (2006) or Brentrup et al. (2000) adapted to…
2.1. Temperate context		… Gp. I	… soil type and plant cover	O	… soil type and irrigation management
2.2. Mediterranean context		… Gp. III	… soil type and plant cover	O	… soil type and irrigation management
2.3. Tropical context		Bouwman and Van Der Hoek (1997) and ECETOC (1994) Gp. II		O	… soil type, irrigation management and rainfalls

× Level of specificity not homogenous enough to consider only one method, *ø* level of specificity which requires a specific methods but for which no method is available to date, *O* level of specificity for which a specific methods could allow reducing the uncertainty

tropical contexts, especially considering the common intensive practices of irrigation in vegetable systems. For on-substrate systems, the methodology developed by Bres (2009) seems the most appropriate, provided that specificities of waste water management are included (closed- and open-loop systems). For each type of N_r field emissions, there is a potential for improvement from using measured data in different contexts to adapting empirical equations, or using mechanistic and dynamic models to develop generic tools. The soil nitrogen balance should be expanded to include the dynamics of organic nitrogen from soil, fertilizers, and amendments. Indeed, soil of vegetable gardens often shows high organic matter content due to frequent and important organic matter inputs. However, difficulties will arise for short crop cycles and particularly in tropical contexts given the quick turnover of nitrogen fluxes.

We identified important potentials for improvement in capturing the variability of cropping systems when assessing the environmental impact of vegetable products through the LCA methodology. However, there will be a tradeoff between the additional work required to follow these recommendations and the benefits in terms of results quality, to be balanced according to users' own interest. One important limitation remains the lack of quantitative data in certain contexts, such as developing countries. Data availability has to be included as a constraint for the development of methods, and different but consistent tiers of estimation tools should be proposed to users, similarly to the IPCC guidelines for GHG inventories.

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